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THE USE OF HIGH TEMPERATURE SUPERCONDUCTORS IN MAGNETOPLASMADYNAMIC SYSTEMS†

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ABSTRACT

The use of Tesla-class high-temperature superconducting magnets may have an extremely large impact on critical development issues (erosion, heat transfer, and performance) related to MPD thrusters and also may provide significant benefits in reducing the mass of magnetics used in the power processing system. These potential performance improvements, coupled with additional benefits of high-temperature superconductivity, provide a very strong motivation to develop high-temperature superconductivity (HTS) applied-field magnetoplasmadynamic (MPD) thruster propulsion systems. The application of HTS to MPD thruster propulsion systems may produce an enabling technology for these electric propulsion systems. This paper summarizes the impact that HTS may have upon MPD propulsion systems.

BACKGROUND

The NASA Lewis Research Center (LeRC) and the Argonne National Laboratory (ANL) have begun a major joint Initiative on Space and Aeronautical Applications of High-Temperature Superconductivity. The initiative is aimed at those high payoff space and aeronautical applications in which HTS is expected to be the key enabling technology. The initiative is based on taking full advantage of complementary basic research and generic technology activities that are currently supported. The effort in this initiative includes system studies to determine the technology requirements and the system impact of HTS, a focused research and technology program to address and solve the unique technology problems associated with the space and aeronautical applications, the development of engineering models of superconducting components, and a technology demonstration activity. The technical strengths of LeRC and ANL are highly complementary in the critical R&D areas required for these applications. LeRC's expertise in composite materials, structures, and cryogenics complements ANL's expertise in superconductivity and electromagnetic component design. Together, these two national research centers form an outstanding and unique team that can meet NASA goals and regain a leadership role for the United States in a key advanced aerospace technology.

A number of promising space and aeronautical applications were identified for evaluation. These applications were selected on the basis of a potentially enabling impact or large benefit to NASA goals and relevance to the roles and capabilities of the two Laboratories. Five HTS applications selected for initial emphasis are:

(1) Magnetoplasmadynamic Propulsion Systems
(2) Microwave Power Transmission
(3) Magnetic Energy Storage for Space Applications
(4) Electromagnetic Launch Technology
(5) Electromagnetic Airport Applications

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These five are briefly described here, along with other promising applications.

Magnetoplasmadynamic Propulsion Systems

The use of HTS magnets is expected to have a major impact on critical development issues related to MPD thruster design. The available experimental and theoretical evidence indicates that high magnetic fields may greatly increase thruster lifetime. Recent tests also show performance enhancements from 57 to 160 percent using high field strength magnets in MPD thrusters. HTS also may provide significant benefits for reducing the mass of magnetics used in the power processing system.

Microwave Power Transmission

An attractive space application of microwave power transmission would involve transmitting large amounts of power, at frequencies near 500 GHz, from Mars synchronous orbit to the Martian surface in support of a future mission. This application is an alternative to landing a reactor on the surface.

Magnetic Energy Storage for Space Applications

A preliminary evaluation of the attributes of HTS magnetic storage indicates that this technology has significant potential for nearer-term low-Earth orbit applications as well as for longer-term space applications.

Electromagnetic Launch Technology

In recent years, NASA-sponsored mission studies have investigated the technical feasibility and merit of using electromagnetic launchers for a variety of to-space and in-space propulsion applications. Results of two recent studies concluded that large-scale mission applications of electromagnetic launchers appear to be not only technically feasible but also economically attractive. The technology assessments of the studies found no insurmountable technical barriers.

Electromagnetic Airport Applications

The technology needed for EM airports is a blend of that used in magnetically levitated (MAGLEV) trains and EM mass drivers. Potential airport applications include takeoff assistance for aircraft, aircraft braking, and MAGLEV systems for surface traffic management. These applications may permit airports of the future to handle an order of magnitude greater traffic with greater safety and no increase in size. Additional benefits are expected to include reduced noise and air pollution around airports. Also, since electromagnetically-assisted takeoff would permit a downsizing of aircraft engines, a considerable savings in aircraft fuel consumption could be realized.

Other Promising Applications

Other applications were also identified that show promise for providing large benefits from the use of HTS. These are:

(1) Shielding from High Energy Charged Particles
(2) Reentry/Aerobraking Magnetic Heat Shield
(3) Orbit Raising Energy Transfer System
(4) Aeropropulsion Applications

INTRODUCTION

This paper focuses on the impact that HTS may have upon MPD propulsion systems--one of the applications described above. MPD thrusters are low-thrust devices with high fuel efficiency that offer the possibility of reasonable transit times to all but the most distant planets. There is no real competition with chemical propulsion systems for attaining Earth orbit; however, these high-thrust systems are not optimal for lunar or interplanetary propulsion. Long travel times or excessive mass in low Earth orbit (LEO) are necessary with high-thrust systems [1]. MPD thruster systems have very low thrust but high specific impulse and can provide thrust continuously. For energetic missions, these high specific impulse thrusters in conjunction with solar or nuclear-electric power systems can significantly reduce spacecraft propellant requirements.

A representative mission application of the MPD thruster would be a lunar-based Mars cargo vehicle [2]. Such a system would require thruster lifetimes of a few thousand hours and a total impulse capability in excess of 10^8 Ns. Since present generation steady-state thrusters, using common space storable propellants, provide a total impulse capability of only 10^4 to 10^6 Ns at thrust efficiencies of about 20 percent, significant gains in electrode lifetime and thruster efficiency are required to meet these mission requirements.

Figure 1 illustrates the current and magnet field distribution in an applied-field MPD arc thruster. The applied arc current between the anode and cathode flows radially with some pluming into the exhaust. The applied magnetic field diverges to form what can be termed a magnetic nozzle. There is also an induced azimuthal magnetic field which is caused by the applied arc current itself. In addition to the applied arc current, there is also an induced azimuthal current. Given the geometry, currents, and fields, there are three basically different thrust mechanisms simultaneously present. For any given MPD thruster design, the thruster mass flow, current, and magnetic field can be adjusted to make any one of these three mechanisms important [3].

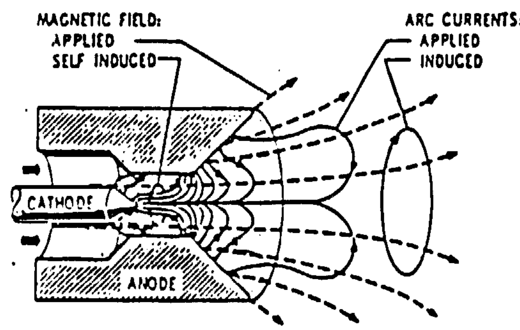


FIG. 1. MPD thruster currents and magnetic fields.

The present state-of-the-art of MPD thrusters is the result of nearly three decades of research and development activity. The most intense effort was undertaken during the 1960s and early 1970s when NASA Lewis, AVCO, McDonnell Douglas, and others developed steady-state, applied-field MPD thrusters in the 10-100 kW range [4,5]. Applied-field thrusters employed electromagnets, permanent magnets, and superconducting magnets [6].

High Tesla-class applied magnetic fields, produced by HTS magnets, will provide increased MPD thruster power density and thrust at high performance. The high magnetic field will produce a strong magnetic nozzle which will replace the extremities of a physical nozzle and thus may minimize the gas dynamic heat transfer losses at the anode. The applied magnetic field is nearly parallel to the cylindrical anode walls, and if the magnetic field is intense enough to produce a fractionally high current azimuthal to the cathode, then the jXB forces are directed away from the walls producing acceleration and containment [7].

Also, high strength applied B-fields in the region of the cathode may possibly be tailored to produce favorable plasma characteristics for long-life electrodes. Increasing electrode lifetime by nearly two orders of magnitude over the present state-of-the-art is crucial for the development of the MPD thruster for planetary cargo vehicle propulsion.

POTENTIAL BENEFITS

The primary prospective benefits of using HTS magnets in MPD arc systems are major increases in thruster lifetime and performance. Other system enhancing benefits include: major mass benefits gained by using HTS power supply magnetics, increased refrigeration system reliability, lower system costs, and other component size and mass reductions.

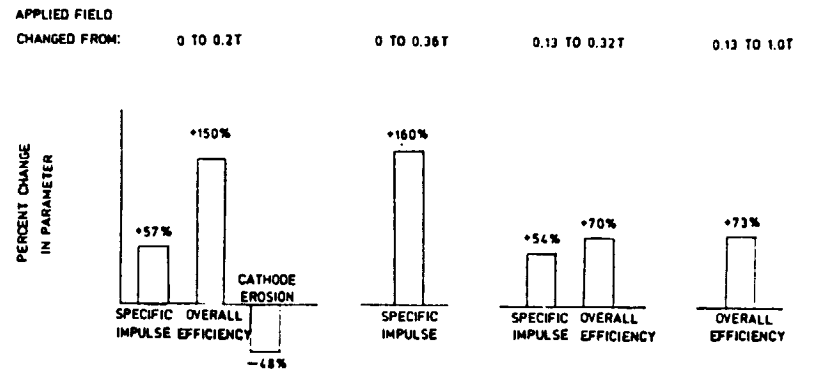
Several papers, some quite recently, have presented experimental MPD thruster results which show substantial and impressive thruster performance improvements in the presence of an applied magnetic field [3,6,8-10] In tests where variations in the applied field level were reported, thruster performance improved with increasing applied field. The specific performance parameters reported and measured were:

- thruster efficiency
- engine thrust
- thruster specific impulse
- erosion behavior

Table I cites five references [6,9,11-13] which show performance enhancement from 57 to 160 percent by using high field strength magnets with the MPD thruster. Evidence of reduced electrode erosion rates was also reported. Major increases in overall thruster efficiency were also reported in experiments using a helium superconducting magnet to provide the applied field. For example, the thrust efficiency of a radiation-cooled MPD thruster was increased by more than 70 percent by increasing the applied field from 0.13 to 1 Tesla using a superconducting magnet [6]. In other experiments using a pulsed megawatt level MPD thruster with a superconducting magnet, the power density and thrust increased dramatically as the applied field was increased. In this case, the power capability was increased by at least a factor of three as the applied field was varied from 0 to 2 T. Clearly, major improvements are in store for applied-field MPD thruster research and technology.

An HTS/MPD propulsion system will strongly enhance the mission capabilities of lunar/Mars cargo vehicles that carry nuclear-electric power systems as well [1,2]. Using an HTS/MPD propulsion system will dramatically reduce the demands for Earth-to-orbit propulsion. However, such a system requires thruster lifetimes of a few thousand hours and a

TABLE I. MPD thruster performance improved due to high applied magnetic field strength.



PROPELLANT:	AMMONIA	ARGON	LITHIUM	ARGON
ARC CURRENT, kA:	10–14	0.7	0.35	≈ 0.4
REFERENCE:	AIAA PAPER 85–2001 87–1001	AIAA PAPER 76–1001	PRINCETON THESIS, D.B. FRADKIN, 1973	AIAA PAPER 71–696

total impulse capability in excess of 10^8 Ns. Demonstrated lifetimes of present generation MPD thrusters are one to three orders of magnitude lower than believed necessary for a lunar/Mars cargo mission. Detailed Mars mission studies have shown that thruster efficiency is also extremely critical for short trip times (from low lunar orbit) and high specific impulse [14]. Hence, to successfully develop the MPD thruster for planetary or orbit raising missions, significant gains in electrode lifetime and thrust efficiency must be realized.

The use of Tesla-class HTS magnets may have an extremely large impact on critical development issues (erosion, heat transfer, and performance) related to the MPD thruster. These potential performance improvements, coupled with other benefits of high-temperature superconductivity (e.g., major mass benefits gained by using HTS power supply magnetics, increased refrigeration system reliability, lower system costs, and other component size and mass reductions), provide a very strong motivation for developing superconducting applied-field MPD thruster propulsion systems.

CRITICAL RESEARCH AND TECHNOLOGY (R&T) ISSUES

Increasing electrode lifetime by nearly two orders of magnitude over the present state of the art is crucial for the development of the MPD thruster for planetary cargo vehicle propulsion. MPD testing to date has shown that thruster life-limiting phenomena are electrode wear and localized insulator erosion. Higher total impulse capability, especially at higher power levels, is limited by cathode erosion.

Cathode erosion mechanisms must be better understood and controlled to demonstrate long life and high total impulse capability. High strength

B-fields in the region of the cathode may possibly be tailored to produce favorable plasma characteristics for long-life electrodes. Hence, experiments should be undertaken to determine if plasma characteristics in the vicinity of the cathode can be tailored by applied magnetic fields to reduce cathode heat transfer and erosion rates. Also, magnetic nozzle/electrode experiments should be undertaken to establish design criteria for thrusters with electrode lifetimes adequate to produce a desired thruster total impulse capability greater than 10^8 Ns.

Based on applied field MPD tests reported so far, there is little doubt that significant increases in thruster performance parameters such as power level, power density, thrust, efficiency, and specific impulse can be anticipated from HTS/MPD thrusters. The main challenge will be to achieve these performance improvements with adequately durable electrodes. For ground-based testing, helium superconducting magnets can provide adequate simulation of HTS magnets; hence all the performance and lifetime technology efforts can proceed in parallel with HTS technology development.

JOINT PROGRAM

The joint NASA LeRC/ANL program efforts will involve system level studies, MPD thruster demonstration tests using helium superconducting magnets, and R&T related to high B-field systems using conventional and HTS magnet materials.

The systems studies will review past R&T related to high power MPD plasma generators, magnetic nozzles, and plasma transport mechanisms. The benefits of using HTS materials in MPD thrusters and power processing equipment will be quantitatively assessed, and a preliminary cost-benefit analysis will be undertaken.

An MPD technology demonstration program will be conducted using helium superconducting magnets to quantify the life extension benefits, performance, and reliability of the high magnetic field technology. The basic technology goals would be to show potential to increase thruster system overall efficiency above 50 percent and to demonstrate that a magnetic nozzle has the potential to increase electrode life so a thruster total impulse capability in excess of 10^8 Ns can be achieved.

Finally, an HTS technology development program will be established, together with other HTS propulsion/power applications, to develop bulk HTS materials for high field strength magnets. The fundamental technology program would provide HTS magnet materials and magnet designs that are relatively stress-insensitive, manufactured in usable forms, and able to withstand quenching under structural loading, high current density, and thermal excursions.

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